

CHARACTERISTIC ASSOCIATION AND PATH COEFFICIENT ANALYSIS OF DIFFERENT MORPHOLOGICAL TRAITS IN SUNFLOWER (HELIANTHUS ANNUUS L.)

Iram Khizar¹, Sobia Niaz², Aiman Akbar³, Rabia Shaheen Niazi⁴, Mahrukh Mumtaz⁵,
Tanzila Aslam⁶, Dr. Zill-E-Huma⁷, Tahir Shahzad⁸, Dr. Abid Ejaz⁹,
Dr. Mian Jahan Zaib Rasheed¹⁰

¹Department of Botany, University of Agriculture Faisalabad, Punjab, Pakistan

²Department of Botany, Bahauddin Zakariya University, Multan, Pakistan

^{3,7,8,9}Department of Botany, University of Sargodha, Sargodha, Pakistan

⁴Department of Biological Sciences, Thal University of Bhakkar, Punjab, Pakistan

⁵Department of Botany, University of Sargodha, Sargodha, Pakistan

⁶Department of Chemistry, Government College Women University Faisalabad, Punjab, Pakistan, Senior Scientific Assistant, Pakistan Navy

¹⁰Department of Botany, University of Sargodha, Sargodha, Pakistan

¹iramkhizar08@gmail.com, ²sobasco786@gmail.com, ³aimanakbar315@gmail.com,
⁴rabia.shaheen@tu.edu.pk, ⁵mahrukh128@gmail.com, ⁶tanzilaaslam@gcwuf.edu.pk,
⁷humashah690@gmail.com, ⁸tahirshahzad174@gmail.com, ⁹abid155yahoo.com,
¹⁰jahanzaibrasheedgc@gmail.com

DOI: <https://doi.org/10.5281/zenodo.22007290>

Keywords

Sunflower, genetic variability, seedling vigor, morphological traits, biomass accumulation, genotype selection, germplasm evaluation, sunflower breeding

Article History

Received: 16 May 2026

Accepted: 12 June 2026

Published: 15 August 2026

Copyright @Author

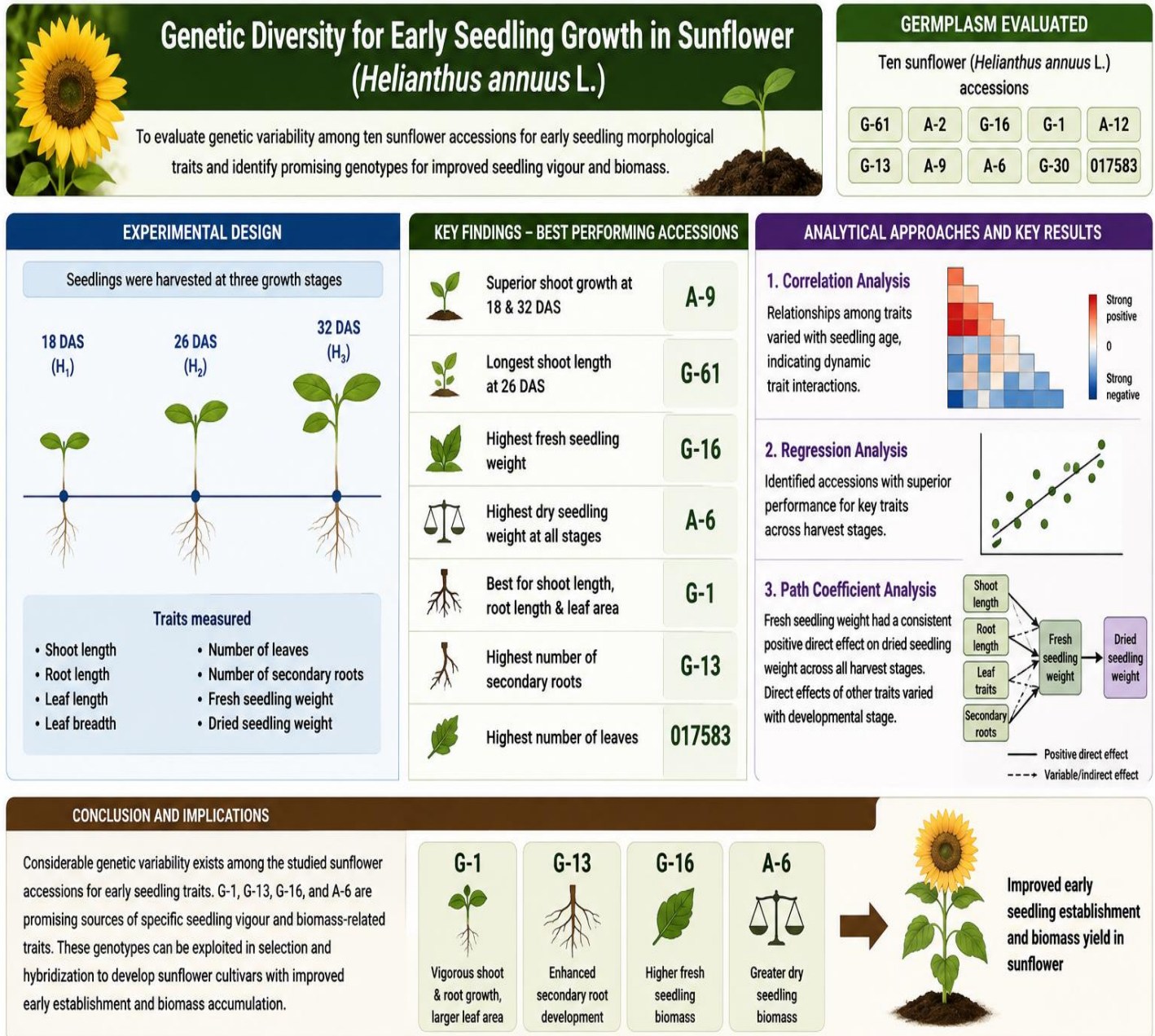
Corresponding Author: *

Tahir Shahzad

Abstract

Genetic diversity for early seedling growth is a critical precondition for developing superior sunflower (*Helianthus annuus* L.) genotypes with improved establishment and biomass yield. The current study compared genetic variation among ten sunflower accessions (G-61, A-2, G-16, G-1, A-12, G-13, A-9, A-6, G-30, and 017583) at three seedling harvest stages: 18, 26, and 32 days after sowing (DAS). Seedling shoot length, root length, leaf length, leaf breadth, number of leaves, number of secondary roots, fresh seedling weight, and dried seedling weight were all documented. Analysis of variance indicated significant variation among accessions, harvest stages, and their interaction for various seedling parameters, demonstrating high genetic diversity and developmental-stage-dependent expression of these attributes. Accession A-9 had superior shoot growth at the first and third harvests, while G-61 had the longest shoot length at 26 DAS. G-16 had the highest fresh seedling weight, but A-6 consistently generated the highest dry seedling weight throughout the harvest phases. According to regression analysis, G-1 outperformed 017583 in terms of shoot length, root length, and leaf area, as well as G-13 in terms of secondary root development. Correlation analysis revealed that connections between morphological features changed with seedling age, emphasizing the dynamic nature of trait relationships throughout early development. Path coefficient analysis revealed that fresh seedling weight had a consistent positive direct effect on

dried seedling weight across all harvest stages, whereas the direct contributions of shoot length, root length, leaf characteristics, and secondary roots varied depending on developmental stage. The results show that the studied sunflower accessions have significant genetic variety, with G-1, G-13, G-16, and A-6 emerging as attractive sources for specific seedling vigour and biomass-related parameters. These accessions could be useful genetic resources for selection and hybridization in sunflower breeding programs that aim to improve early seedling establishment and biomass buildup.



Graphical abstract genetic variability and trait association analysis reveal promising sunflower accessions for enhanced early seedling vigor and biomass accumulation

INTRODUCTION

Edible oil is one of the important commodities of everyday use. Only 30% of edible oil requirements of Pakistan are met through local production, and the other 70% of the country's requirements are met through import, costing huge amounts of foreign exchange. The imported edible oils are mainly palm and soybean oil. But the problem of shortage of edible oil still remains. The position of Pakistan's oil production is more favourable than previously, but continuous improvement in the productivity of oil production is desirable in the wake of ever-increasing human population (Rana et al., 2022). Similarly, its average yield has also increased considerably with fluctuations due to use of sub-optimal inputs, poor quality seed, cultivation on marginal lands, unfavorable climatic conditions, etc. Presently sunflower has become the most important oil seed crop (Casadebaig et al., 2022). The growth of sunflower as an oilseed crop has revealed that soybean with both increasing productions over 6 folds since the 1930's (Rauf et al., 2017).

Sunflower seed is rich in oil contents between 40-53 % and protein 23 %. Furthermore, it is better in quality of oil, having a high percentage of linoleic acid and a low percentage of linolenic acid, which is the most desired one which is not available in any other oil. Sunflower seed cake has proved to be good quality feed for dairy animals and particularly for poultry birds. For sunflower early spring frost and late summer cool situations are common. Sunflower is a drought tolerant and short duration crop and has a wider range of adaptability (Mu et al., 2025). Essential fatty acid, rich in protein and the sunflower seeds are used in medicine. These nutrients are essential for brain, eyes and good health of the nerves. It has 10% linoleic acids and 90% oleic acid in its oil content. Sunflower is grown with its chief objective to have high protein and oil value (Rauf et al., 2017).

The genetic variations provided opportunities to the plant breeders to create new and modified cultivars having the necessary traits, including those that are preferred by the farmer and those

preferred by the breeder (such as photosensitivity, pest and disease resistance). From the very start of the agriculture to fulfill the sustenance food requirements, natural genetic variations have been oppressed between crop species and now it is focusing on the better food for increasing populations. Accessibility and easy approach to genetic resources are making the global food production chain more sustainable (Begna, 2021). As the demand of sunflower utilization is increasing day by day, it is necessary to make efforts for the development of high yielding sunflower cultivars. The differences between the individuals of the breeding material are called Genetic Variability. It is a reflection of the variability of some individual genotypes of a given population. It is helpful for plant breeder to adopt proper breeding procedure. Data on the amount and type of genetic diversity available in an agricultural species is vital for crop improvement and development programmes, as well as for the improvement of the desired traits (Swarup et al., 2021).

Seed yield is dependent on many traits, which are polygenic in nature and it is hard to make direct selection for these traits. Through associated component traits to improve seed yield indirect selection is possible. Simple correlation analysis does not reveal the mutual relationships among these characters related to the plants. Path-coefficient analysis quantifies direct and indirect contributions of constituents of a complex trait such as yield (Radanović et al., 2018). Path coefficient analysis is a way that the genotypic correlation is divided into direct and indirect effects of independent variable to dependent variable. As a result, for the selection of desirable traits for attaining the more explained results the path analysis techniques can be used (Kumar et al., 2018).

Materials and Methods

Germplasm collection

Ten sunflower (*Helianthus annuus* L.) accessions were collected from Oilseed Research Group of the Department of Plant Breeding and Genetics

in University of Agriculture, Faisalabad. The study included ten sunflower (*Helianthus annuus* L.) accessions, namely G-61, A-2, G-16, G-1, A-12, G-13, A-9, A-6, G-30, and 017583.

Experimental design

Harvesting was done at three stages and data obtained. The first harvest (H1) was done 18 days after sowing (DAS), the second harvest (H2)

was done 26 DAS and the third harvest (H3) was done at 32 DAS. Observations were made separately for each accession and each replication at each harvest. The information gathered during the three harvests was then compared with regression analysis to find out the best time to harvest for the best growth stage for evaluating seedling performance among the accessions of sunflower.



Figure 1: A view of experimental design area in wire house

Shoot length (cm)

Seedling shoot lengths (cm) determined on a measuring scale per accession per replication per harvest.

Root length (cm)

The lengths of roots of seedlings were measured per accession per replication per harvest in cm on measuring scale.

Leaf length (cm)

Seedling length (length of leaves) was measured per replication per accession and per harvest in cm with measuring scale.

Leaf width (cm)

Leaf width of seedlings per accession per replication per harvest were recorded which was measured in cm with measuring scale.

Number of leaves

Leaves of selected per accession were harvested and counted per replications.

The mass of seedlings (g)

Each accession's seedlings were harvested by the electrical balance (Setra, BL-410S) and the weight was measured in grams and fresh weight.

Dry weight

Seedlings were kept in separate kraft paper bags and placed in oven at 70C for 24 hours. Then weights of dry seedlings of each accession per replication per harvest were recorded by using electrical balance (Setra, BL-410S).

Biometrical Analysis**Path analysis**

In order to find the direct and indirect effects of various traits on dry seedling weight which was kept as resultant variable (effect), path coefficient analysis was run. Path diagram showing the effects of various traits on resultant variable (dry weight) is presented.

Regression analysis

The equation has the form $Y=a + bX$, where Y is the dependent variable (that's the variable that goes on the Y axis), X is the independent variable (i.e. it is plotted on the X axis), b is the slope of the line and a is the y-intercept

Analysis of Variance

Analysis of variance for *Helianthus annuus* L. accessions for various characters under three harvests

Results**Number of secondary roots per plant**

Results for analysis of variance and comparison of means among treatments and accessions for number of secondary roots are presented in Table 4.6. Analysis of variance showed significant differences for accessions, treatments and their interaction in *Helianthus annuus* L. number of secondary roots of all accessions in treatments were almost similar with each other. Harvest 1 showed that among accessions, A-9 had maximum shoot length followed by G30 and G-16. Accession 017583 had minimum shoot length followed by accessions A-12, A-2 as presented in graph 4.6.2. Accessions showed significant differences for seedling length for first harvest. Harvest 2 showed that accession G-61 had maximum shoot length followed by accessions A-9 and G-13. Accession 017583 had minimum shoot length followed by accessions A-6 and G16. Accessions showed significant differences for seedling length for second harvest. Harvest 3 showed that accession A-9 had maximum shoot length followed by accessions G-30 and G-16. Accession A-2 has minimum shoot length followed by accessions A6 and G-1. Accessions showed significant differences for seedling length for third harvest.

Table 1: Analysis of variance of *Helianthus annuus* L. accessions for number of secondary roots per plant under various harvests

SOV	DF	SS	MSS	Fcal
Accessions (A)	9	403.89	44.8772	25.76**
Harvests (H)	2	107.04	53.518	30.72**

H × A	18	1126.93	62.607	35.93**
Error	60	104.53	1.7422	
Total	89	1742.39		

SOV= Sources of variations, DF= Degrees of freedom, SS= Sum of square and MSS= Mean sum of square, F_{cal}= F calculated, *=Significant, **= Highly significant

Table 2: Analysis of variance of *Helianthus annuus* L. accessions for fresh seedling weight under various harvests

SOV	DF	SS	MSS	Fcal
Accessions (A)	9	3.61902	0.40211	138.29**
Harvests (H)	2	0.59789	0.29894	102.81**
H × A	18	1.21076	0.06726	23.13**
Error	60	0.17446	0.00291	
Total	89	5.60213		

SOV= Sources of variations, DF= Degrees of freedom, SS= Sum of square and MSS= Mean sum of square, F_{cal}= F calculated, *=Significant, **= Highly significant





Environmental correlation under all harvests

Environmental correlation of root length with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing root length had negative non-significant correlation with shoot length. Under harvest 2 i.e. after 26 days of sowing root length had negative and highly significant correlation with shoot length. Under harvest 3 i.e. after 32 days of sowing root length had negative and non-significant correlation with shoot length.

Environmental correlation for leaf length with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf length had positive and non-significant correlation with shoot height and root length. Under harvest 2 i.e. after 26 days of sowing leaf length had negative and highly significant correlation with shoot height and root length. Under harvest 3 i.e. after 32 days of sowing leaf length had positive and non-significant correlation with root length. It also had negative and non-significant correlation with shoot length.

Environmental correlation for leaf width with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf width had negative and significant correlation with root length and it had positive non-significant correlation with shoot length. It had negative non-significant correlation with leaf length. Under harvest 2 i.e. after 26 days of sowing leaf width had negative and non-significant correlation with shoot height, root length and leaf length. Under harvest 3 i.e. after 32 days of sowing leaf width had positive and non-significant correlation with shoot length and leaf length. It had negative and non-significant correlation root length.

Environmental correlation for No. of leaves per plant number with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing No. of leaves per plant had positive and significant correlation with leaf length. It also had positive

and non-significant correlation with root length and leaf width. It had and non-significant correlation with shoot length. Under harvest 2 i.e. after 26 days of sowing No. of leaves per plant had positive and highly significant correlation with leaf width. It had negative and significant correlation with root length. It had negative non-significant correlation with shoot length and leaf length. Under harvest 3 i.e. after 32 days of sowing No. of leaves per plant had negative and non-significant correlation with shoot length, leaf length and leaf width. It had positive and non-significant correlation with root length.

Environmental correlation for No. of secondary roots per plant with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing No. of secondary roots per plant had positive and non-significant correlation with shoot length. It also had negative and non-significant correlation with leaf width, root length, leaf length and No. of leaves per plant. Under harvest 2 i.e. after 26 days of sowing No. of secondary roots per plant had positive and non-significant correlation with shoot length and leaf width. It had negative and non-significant correlation with root length, leaf length and No. leaves per plant. Under harvest 3 i.e. after 32 days of sowing No. of secondary roots per plant had negative and highly significant correlation with root length. It had positive and non-significant correlation with shoot length, leaf length and leaf width. It had negative and non-significant correlation with No. of leaves per plant.

Environmental correlation for fresh seedling weight with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing fresh seedling weight had positive and non-significant correlation with shoot length, root length, leaf length and No. leaves per plant. It had negative and non-significant correlation with No. of secondary roots per plant and leaf width. Under harvest 2 i.e. after 26 days of sowing fresh seedling weight had positive and significant correlation with No. leaves per plant and it had

negative and highly significant correlation with shoot length, root length and leaf length. It had positive and non-significant correlation with No. of secondary roots per plant and leaf width. Under harvest 3 i.e. after 32 days of sowing fresh seedling weight had positive and highly significant correlation with leaf width. It had positive and non-significant correlation with root length and leaf length. It had negative and non-significant correlation with shoot length, No. of leaves per plant and No. of secondary roots per plant.

Environmental correlation for dry seedling weight with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing dry seedling weight had positive and highly significant correlation with fresh seedling weight. It had positive and non-significant correlation

with, shoot length, leaf length, No. of leaves per plant, root length. It had negative and non-significant correlation with leaf width and No. of secondary roots per plant. Under harvest 2 i.e. after 26 days of sowing dry seedling weight had positive and non-significant correlation with shoot length, root length, leaf length, leaf width, No. of secondary roots per plant and fresh seedling weight. It had negative and non-significant correlation with No. of leaves per plant. Under harvest 3 i.e. after 32 days of sowing dry seedling weight had negative and significant correlation with No. of leaves per plant. It had positive and significant correlation with shoot length, root length, leaf length, leaf width and fresh seedling weight. It had negative and non-significant correlation with No. of secondary roots per plant.

Table 4: Environmental correlation of various traits in Sunflower accessions traits for harvest 1

	SL	RL	LL	LW	L. NO.	SR
RL	-0.249					
LL	0.149	0.327				
LW	0.233	-0.443*	-0.253			
L. NO.	-0.3	0.194	0.458*	0.089		
SR	0.03	-0.282	-0.289	-0.016	-0.016	
FW	0.173	0.204	0.258	-0.058	0.237	-0.118
DW	0.173	0.204	0.258	-0.058	0.237	-0.118

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 5: Environmental correlation of various traits in Sunflower accessions traits for harvest 2

	SL	RL	LL	LW	L. NO.	SR	FW
RL	-0.119**						
LL	0.010**	0.314**					
LW	-0.102	-0.217	-0.22				
L. NO.	-0.218	-0.045*	-0.2	0.326**			
SR	0.031	-0.866	-0.204	0.149	-0.169		
FW	0.164**	-0.028**	-0.225**	0.459	0.222*	0.038	
DW	0.267	0.099	0.175	0.029	-0.391	0.06	0.302

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 6: Environmental correlation of various traits in Sunflower accessions traits for harvest 3

	SL	RL	LL	LW	L. NO.	SR	FW
RL	-0.559						
LL	-0.53	0.626					
LW	0.218	-0.051	0.145				
L. NO.	-0.044	0.356	-0.019	-0.588			
SR	0.035	-0.281**	0.033	0.335	-0.327		
FW	-0.516	0.472	0.596	0.280*	-0.38	-0.164	
DW	0.125	0.07	0.028	0.268	-0.218*	-0.116	0.049

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Path analysis

Direct and indirect effects of shoot length on dry seedling weight under all harvests

Under harvest 1 i.e. after 18 days of sowing shoot length had negative direct effect on dry seedling weight. Indirect effect of shoot length through root length, leaf length, leaf width, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through No. of leaves per plant. Under harvest 2 i.e. after 26 days of sowing shoot length had negative direct effect on dry seedling weight. Indirect effect of shoot length through root length, leaf width, No. of leaves per plant, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through leaf length. Under harvest 3 i.e. after 32 days of sowing shoot length had positive direct effect on dry seedling weight. Indirect effect of shoot length through root length, leaf length, leaf width, No. of leaves per plant, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through root length only.

Direct and indirect effects of Root length on dry seedling weight under all harvests

Under harvest 1 i.e. after 18 days of sowing root length had negative direct effect on dry seedling weight. Indirect effect of root length through shoot length, No. of leaves per plant, No. of secondary roots and fresh shoot weight was

positive and it had negative indirect effect on dry seedling weight through leaf length and leaf width. Under harvest 2 i.e. after 26 days of sowing root length had positive direct effect on dry seedling weight. Indirect effect of root length through leaf length, leaf width, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through shoot length and No. of leaves per plant. Indirect effect of root length through shoot length, leaf length, leaf width, No. of leaves per plant, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through No. of leaves per plant only.

Direct and indirect effects of leaf length on dry seedling weight under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf length had positive direct effect on dry seedling weight. Indirect effect of leaf length through root length, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through shoot length, leaf width and No. of leaves per plant. Under harvest 2 i.e. after 26 days of sowing leaf length had negative direct effect on dry seedling weight. Indirect effect of leaf length through leaf width and fresh seedling weight was positive and it had negative indirect effect on dry seedling weight through shoot length, root length, No. of secondary roots and No. of leaves per plant. Under harvest 3 i.e. after 32 days of sowing leaf

length had negative direct effect on dry seedling weight. Indirect effect of leaf length through root length, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through shoot length, leaf width and No. of leaves per plant.

Direct and indirect effects of leaf width on dry seedling weight under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf width had negative direct effect on dry seedling weight. Indirect effect of width through shoot length leaf length, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through root length and No. of leaves per plant. Under harvest 2 i.e. after 26 days of sowing leaf width had positive direct effect on dry seedling weight. Indirect effect of leaf width through root length, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through shoot length, leaf length and No. of leaves per plant. Indirect effect of leaf width through shoot length leaf length, leaf width, No. of leaves per plant, No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through root length only.

Direct and indirect effects of No. of leaves per plant on dry seedling weight under all harvests

Under harvest 1 i.e. after 18 days of sowing No. of leaves per plant had negative direct effect on dry seedling weight. Indirect effect of No. of leaves per plant through root length, leaf length, No. of secondary roots and fresh seedling weight was positive and it had negative indirect effect on dry seedling weight through leaf width and shoot length. Under harvest 2 i.e. after 26 days of sowing No. of leaves per plant had negative direct effect on dry seedling weight. Indirect effect of No. of leaves per plant through leaf width, shoot length, root length, and fresh seedling weight was positive and it had negative indirect effect on dry seedling weight through leaf length and No. of secondary roots. Under harvest 3 i.e. after 32 days of sowing No. of leaves per plant had

negative direct effect on dry seedling weight. Indirect effect of No. of leaves per plant through root length, leaf width, shoot length, leaf length, was positive and it had negative indirect effect on dry seedling weight through No. of secondary roots and fresh seedling weight.

Direct and indirect effects of No. of secondary roots per plant on dry seedling weight under all harvests

Under harvest 1 i.e. after 18 days of sowing No. of secondary roots per plant had positive direct effect on dry seedling weight. Indirect effect of No. of secondary roots per plant through leaf length and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through shoot length, root length, leaf width and No. of leaves per plant. Under harvest 2 i.e. after 26 days of sowing No. of secondary roots per plant had negative direct effect on dry seedling weight. Indirect effect of No. of secondary roots per plant through leaf length and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through shoot length, root length, leaf width and No. of leaves per plant. Indirect effect of No. of secondary roots per plant through shoot length, leaf width and fresh seedling weight was positive and it had negative indirect effect on dry seedling weight through root length, leaf length and No. of leaves per plant.

Direct and indirect effects of fresh seedling weight on dry seedling weight under all harvests

Under harvest 1 i.e. after 18 days of sowing fresh seedling weight had positive direct effect on dry seedling weight. Indirect effect of fresh seedling weight and No. of secondary roots and fresh shoot weight was positive and it had negative indirect effect on dry seedling weight through root length, shoot length, leaf width and No. of leaves per plant. Under harvest 2 i.e. after 26 days of sowing fresh seedling weight had positive direct effect on dry seedling weight. Indirect effect of fresh seedling weight through leaf width was positive and it had negative indirect effect on

dry seedling weight through root length, shoot length, leaf length, No. of leaves per plant and No. of secondary roots. Under harvest 3 i.e. after 32 days of sowing fresh seedling weight had positive direct effect on dry seedling weight. Indirect effect of fresh seedling weight through shoot length, leaf width, No. of secondary roots per plant and fresh seedling weight was positive and it had negative indirect effect on dry seedling weight through root length, leaf length and No. of leaves per plant.

Regression analysis

Regression analysis for three harvests. Shoot length is maximum for accession G-1 followed by

accession A-6. Maximum root length was seen in accession G-1 followed by accession G-13. Maximum leaf area was observed by accession G-1 followed by accession 017583. Maximum No. of leaves were observed in all harvests by accession 017583 followed by accession G-13. Maximum No. of secondary roots were observed by accession G-13 followed by accession A12. Highest fresh seedling weight was observed by accession G-16 followed by accession G-1 and maximum dry seedling weight was observed in accession A-6 followed by accession G-16 in all harvests.

Table 7: Direct (Bold) and indirect effects of various traits on dry seedling weight in *Helianthus annuus* L. accessions under harvest 1

Trait	SL	RL	LL	LW	L. NO.	SR	FW
SL	-1.272	4.342	2.456	9.276	-5.882	2.871	0.101
RL	4.098	-1.347	-5.835	-3.396	3.376	1.411	0.305
LL	-5.569	1.402	5.609	-1.869	-1.192	6.793	0.392
LW	2.284	-8.858	2.03	-5.166	-1.019	3.562	0.272
L. NO.	-5.181	3.15	4.631	-3.648	-1.443	8.716	0.362
SR	-4.051	-2.109	4.227	-2.041	-1.396	9.016	0.692
FW	-1.282	-4.106	2.198	-1.406	-5.231	6.243	1

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No of secondary roots, FW= Fresh weight, DW= Dry weight

Table 8: Direct (Bold) and indirect effects of various traits on dry seedling weight in *Helianthus annuus* L. accessions under harvest 2

Trait	SL	RL	LL	LW	L. NO.	SR	FW
SL	-1.979	0.38	-0.146	0.397	0.356	0.763	0.212
RL	-1.258	0.598	0.118	0.15	-0.006	0.546	-0.435
LL	-0.295	-0.072	-0.979	0.333	-1.349	-0.11	2.522
LW	-0.784	0.089	-0.326	1.002	-1.96	0.19	1.619
L. NO.	0.23	0.001	-0.431	0.642	-3.06	-0.36	2.582
SR	1.055	-0.227	-0.075	-0.133	-0.77	-1.432	0.986
FW	-0.132	-0.082	-0.779	0.512	-2.494	-0.446	3.169

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 9: Direct (Bold) and indirect effects of various traits on dry seedling weight in *Helianthus annuus* L. accessions under harvest 3

Trait	SL	RL	LL	LW	L. NO.	SR	FW
SL	0.079	-0.007	0.042	0.068	0.388	0.104	0.039

RL	0.004	-0.134	0.078	0.047	-0.485	0.486	0.016
LL	-0.012	0.037	-0.284	-0.015	-0.129	0.372	0.153
LW	-0.021	0.025	-0.016	-0.253	-0.18	-0.009	-0.076
L. NO.	-0.035	-0.075	-0.042	-0.053	-0.862	0.599	0.138
SR	0.008	-0.065	-0.106	0.002	-0.519	0.996	0.105
FW	0.006	-0.004	-0.091	0.04	-0.249	0.218	0.478

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 10: Regression analysis of various accessions of *Helianthus annuus* L. under harvest 1, 2 and 3

Genotype	SL	RL	LA	L. NO.	SR	FW	DW
G61	0.519961	-0.2988	0.05144	0.023256	-0.47093	0.008992	0.009901
A2	0.233953	-0.2149	0.04849	0.003876	0.098837	0.009806	0.017719
G16	0.038566	-0.2797	-0.02028	0.015504	-0.61047	0.012035	0.020333
G1	1.101163	0.14438	0.08716	0.021318	-0.42829	0.011202	0.00712
A12	0.406667	-0.1324	0.04097	0.015504	0.149225	0.001124	0.009407
G13	0.544186	0.05736	0.04129	0.106589	0.304264	0.011977	0.010581
A9	0.110271	-0.3008	-0.06072	-0.10271	-1.0407	0.001182	0.016527
A6	0.61531	-0.0785	0.04868	-0.027132	-0.75969	0.007267	0.02845
G30	0.092054	-0.1368	-0.09374	-0.00775	-0.85078	-0.0575	-0.01455
17583	0.171124	-0.2258	0.06449	0.118217	-0.21705	-0.00389	0.011841

SL= Shoot length, RL= Root length index, LA= Leaf area, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

DISCUSSION

Number of Secondary Roots

There were highly significant differences in the number of secondary roots among the sunflower accessions, harvest stages, and accession × harvest interaction, suggesting that there was a good amount of genetic variability among the germplasm evaluated in the present investigation. There was a large amount of variation for all the root-related traits, indicating that the accessions tested have different genetic potentials for early seedling establishment, which is a key requirement for better nutrient acquisition and drought tolerance. Prior studies on sunflower breeding programs have also confirmed that there is a considerable amount of variation among the genomic types, and it is necessary to select and improve the crops (Arshad et al., 2007; Riaz et al., 2019). During the first and third harvest, accession A-9 had the highest number of secondary roots while accession G-61 performed better during the

second harvest. These differences suggest that proliferation of roots is not only a function of the genotype, but also of developmental stage. Sasikala (2000) and Rani (2016) reported similar genotype-dependent variation in sunflower, and suggested that root and vegetative traits should be taken into account together when selecting superior breeding material since they contribute indirectly to the productivity of the plant as better resource utilization. The strong accession × harvest interaction indicates that root traits are age dependent. Thus, data from several developmental stages give a better estimate of genetic potential than data from a single developmental stage. A similar trend was also reported recently, with emphasis on the efficiency of genotype selection in the stable sunflower crop culture through repeated evaluation during the development of the crop (Sasikala et al., 2025).

Fresh Seedling Weight

Significant differences were found among accessions in sunflower for fresh seedling weight and between the various stages of harvest, indicating that the creation of biomass at early seedling stages is genetically highly controlled. The fresh seedling weight of the G-16 and G-1 accessions was significantly higher than all other accessions, suggesting high early growth potential. The positive correlation between fresh and dry seedling weight indicates that strong seedlings had more structural biomass. Velazquez et al. (2017) and Sakham (2017) observed similar relationships in sunflower where the biomass related traits were directly correlated with economically important traits and suggested their use as indirect selection criteria in breeding programme. Similarly, Marin et al. (2025) found that traits directly related to biomass production showed high positive correlations with plant productivity and, thus, should be placed more weight in the process of genotype selection. Recent path coefficient analysis also showed that the biomass-related characters had significant direct effect on yield and their performance was more reliable than the correlation coefficient alone (Pekcan et al., 2022; Markulj Kulundžić et al., 2025).

Dry Seedling Weight

The dry seedling weight was always greatest for accession A-6, indicating greater physiological efficiency and assimilate accumulation, followed by accession G-16. This may be due to the efficient partitioning of assimilates from the actively growing leaves to the structural tissues because of these accessions. Generally, more dry matter accumulation during the seedling stage will improve plant establishment and the likelihood of better field performance. The same findings were observed by Lagiso et al. (2021) who reported that traits related to biomass showed positive direct effects on seed yield, and therefore were useful in sunflower improvement programmes. Increased production and partitioning of assimilates towards economically important organs (Falchi et al., 2020; Fernie et

al., 2020) is achieved in the end to improve crop productivity in these traits.

Environmental correlation of seedling traits

The observed variation indicates that trait associations change in size and direction with developmental progression in young plants. Weight of fresh seedlings was also positively related to weight of dry seedlings, which is a known fact that more fresh mass equals more dry mass. Similar relations are cited by Bojarian et al. (2019) and Al-Ashkar et al. (2021) who found that the positive correlation of morphological traits could be exploited simultaneously in the indirect selection because of their complementary contribution towards the productivity of the plant. Similarly, Devi et al. (2017) and Aman et al. (2020) found that the traits that showed significant positive correlation with yield also had a significant direct effect by path coefficient analysis, which will enhance the efficiency of breeding programmes. However, during 3rd harvest, a negative correlation between number of leaves per plant and dry seedling weight shows that the more leaves the more weight does not necessarily lead to the more biomass. In contrast, biomass production relies on the integrated action of leaf growth, photosynthetic performance and partitioning of assimilation. Martínez-Vilalta et al. (2023) observed similar, and concluded that individual morphological traits should be explained in concert, not in isolation, since morphological traits are linked in complex ways that ultimately determine plant productivity. This conclusion favors the application of integrated correlation and path coefficient analysis for the identification of superior criteria in sunflower breeding programmes for early establishment and biomass production (Radić et al., 2021; Markulj Kulundžić et al., 2025).

Path Coefficient Analysis

Effect of Shoot Length

The present study showed that shoot length had a negative direct effect on the dry seedling weight at the first and second harvest (18 DAS and 26

DAS) but a positive direct effect at the third harvest (32 DAS). This means that the early shoot elongation period may not necessarily be a time when dry matter is being accumulated, since assimilates are being directed more towards elongation than towards growth. As seedlings grew older, however, shoot growth was positively related to biomass production of structure. Shoot length had positive indirect effects on other morphological traits (root length, leaf width, secondary roots and fresh seedling weight), supporting its contribution to seedling vigor despite having negative direct effects in the first two harvests, demonstrating that shoot elongation contributes indirectly to seedling vigor via the other morphological traits. This was also noted by OlaOlorun et al. (2021) who found that shoot-related traits had indirect effect on seed yield because of their correlation with biomass accumulation and other yield components. Similarly, Homulle et al. (2022) showed that traits with high indirect effects must not be neglected for their selection as they play a significant role in overall plant growth and yield.

Effect of Root Length

Root length had variable direct effects on harvest stage, suggesting that root length's contribution to dry seedling weight was influenced by seedling development. The positive indirect effects of root length on fresh seedling weight, leaf traits, and shoot length indicate that root length is associated with higher vegetative growth because of the increased water and nutrient uptake. Root system development is especially critical in early crop growth to ensure ability to withstand moisture stress and to make soil nutrients available to the crop in an efficient manner. The authors of Mathew et al. (2019) found traits of roots to be significantly related to biomass production and thus suggested that they are given more importance in genotype evaluation. In agreement with this, Bhat et al. (2023) showed that enhancing root growth has a considerable impact on the health and growth of plants.

Effect of Leaf Area

Leaf area had both positive and negative direct effects which varied according to the harvest stage, suggesting that the effect on dry seedling weight changes as seedling development proceeds. The direct effects were variable, but fresh seedling weight and shoot length often had positive indirect effects, indicating that an increase in photosynthetic surface area may lead to an increase in assimilate production which in turn will lead to more biomass. The leaves which do photosynthesis have a basic role in determining the productivity of the plant since they control the production of carbohydrates necessary for growth and development. In recent studies of sunflower, the traits related to leaves were found to be positively correlated with the biomass accumulation and yield in combination with other vegetative traits (Awais et al., 2017; Ren et al., 2025).

Effect of Number of Leaves per Plant

Dry seedling weight as a response to the number of leaves per plant was mostly negatively related in all three harvest periods. The result indicates that biomass can only be increased by increasing the number of leaves if they can be made to grow larger and is more efficient in photosynthesis. The positive indirect effects measured by the shoot length, fresh seedling weight and secondary root number, however, suggest that leaf number has an indirect influence on seedling growth in relation to vigour of vegetative growth. The same has been reported by Veiter et al. (2018) who stated that the combined effect of individual morphological characters must be analysed as they form part of a whole and their combined contribution will rely on interaction with other growth-related characters.

Moderate effect of Secondary Roots

The second order roots had a strong positive direct effect in the first harvest but moderate to negative direct effects in later harvests. This discovery indicates that the development of secondary roots is especially critical at the

seedling stage when the initial growth of the plants depends on how fast they are able to absorb nutrients and water. Additionally, the secondary roots provided positive indirect effects by means of fresh seedling weight, shoot length, and leaf area, further indicating the significance of secondary root development in the process of above-ground biomass accumulation. In line with this, Jocković et al. (2024) found that root structure was a key contributor to better growth of sunflower and identified root traits as potential selection criteria for breeding drought-tolerant and early vigorous sunflowers.

Effect of Fresh Seedling Weight

The weight of fresh seedlings positively and constantly affected dry seedling weight at every harvesting stage. This shows that fresh biomass is the main factor affecting dry matter production in early growth stages of sunflower. The significant indirect paths gained via shoot length, root length, leaf area and secondary roots also show that the fresh biomass reflects the combined effect of several morphological traits. The results are in accordance with the earlier studies which suggest that fresh biomass is one of the most reliable indicators of plant growth as it is an indicator of efficient utilization of plant resources and active physiological processes (Lambers et al., 2019; Gallegos-Cedillo et al., 2021). Therefore, fresh seedling weight can be used effectively as an indirect selection criterion for sunflower seedling vigor improvement program.

Importance of Path Coefficient Analysis in Sunflower Breeding

In the present study, it is shown that path coefficient analysis yields much more information than the simple correlation analysis since it separates direct effect from indirect effect among interrelated traits. Path analysis can be used to determine the true contribution of each character to the dependent character, so that the desirable breed can be obtained by selecting characters with real biological significance. In general, the most important characteristics

which influenced dry seedling weight were: fresh seedling weight, shoot length, root length, leaf area, and secondary root development. The traits might thus be appropriate selection criteria to enhance early seedling vigor and biomass accumulation in sunflower. The same conclusions have been made by (Komel & Razzaq, 2019; Tahir et al., 2019) who have highly stated that the use of correlation and path coefficient analysis significantly enhances the efficiency of selection of superior sunflower genotypes.

Regression Analysis of Seedling Morphological Traits

The regression coefficients revealed that G-1 accession had the best shoot length, root length and leaf area, indicating excellent vegetative growth in the seedling stage. It ensures strong shoot and root growth which boosts photosynthetic potential and ability to absorb nutrients and water, resulting in fast seedling establishment. A similar correlation between vegetative growth characteristics and total plant production has been reported by Varalakshmi et al. (2022) who recommended that shoot and root traits can serve as good predictor of the performance of genotypes at the early growth stage. Accession 017583 yielded the most leaves per plant and G-13 had the most secondary roots. The results show that there are genetic differences among accessions in their ability to develop specific morphological traits. A large secondary root system will aid in the uptake of soil moisture and soil nutrients, and an increase in leaf number will increase photosynthetic capacity if there is enough leaf expansion. (Jan et al., 2025) also found that root architecture and leaf development are both major factors that affect biomass production and should be taken into account while selecting a genotype. G-16 had the highest fresh seedling weight among the accessions evaluated, and the dry seedling weight from the three harvest stages was highest with A-6. The results indicate that A-6 had greater assimilate accumulation and biomass partitioning efficiency in early seedling growth.

The amount of dry biomass accumulated is directly related to efficient photosynthesis and resource utilization, and is one of the most reliable measures of vigor in seedlings. Similarly, Aloui et al. (2025) reported that biomass-related traits have a direct impact on the overall plant productivity, hence should be emphasized more in sunflower breeding programmes. Variation between accessions suggests that no particular genotype was best for all morphological characters. Rather, each accession had unique benefits, and the potential exists to create a hybrid seedling with even better characteristics. Consistent with the suggestion of Mariyam et al. (2024) for using genetically diverse accessions as parents for expanding the genetic diversity in sunflower breeding populations.

Conclusion

The present investigation demonstrated substantial genetic variability among the ten sunflower accessions for early seedling morphological and biomass related characters. Significant differences among accessions, harvest stages and accession × harvest interactions confirmed that the expression of seedling traits was strongly influenced by both genotype and developmental stage. The results also showed that no single accession was superior for all traits, indicating the presence of trait-specific genetic potential within the evaluated germplasm. G-1 outperformed the other accessions in expressions of shoot length, root length, and leaf area, whereas G-13 produced the most secondary roots. Accession 017583 had the most number of leaves, while G-16 had the highest fresh seedling weight. A-6 consistently formed the highest dry seedling weight at all three harvest stages, indicating improved early biomass increase and assimilate partitioning. Correlation study revealed that connections between seedling attributes changed with developmental stage, emphasizing the need of evaluating genotypes throughout multiple growth stages. Path coefficient analysis found that fresh seedling weight was the most consistent positive direct contributor to dried

seedling weight throughout all harvests, but the direct effects of shoot length, root length, leaf characteristics, number of leaves, and secondary roots changed with seedling age. As a result, fresh seedling weight, along with shoot and root traits, can be valuable selection criteria for increasing early seedling vigour. Overall, G-1, G-13, G-16, and A-6 are excellent genetic resources for sunflower improvement due to their complimentary benefits in vegetative growth, root development, and biomass accumulation. Their adoption into future breeding and hybridization programs could extend the genetic base and aid in the development of sunflower genotypes with better early establishment and robust biomass output.

REFERENCES

- Riaz, A., Nadeem Tahir, M.H., Rizwan, M., Fiaz, S., Chachar, S., Razzaq, K., Riaz, B. and Sadia, H., 2019. Developing a selection criterion using correlation and path coefficient analysis in sunflower (*Helianthus annuus* L.). *Helia*, 42(70), pp.85-99.
- Arshad, M., Ilyas, M.K. and Khan, M.A., 2007. Genetic divergence and path coefficient analysis for seed yield traits in sunflower (*Helianthus annuus* L.) hybrids. *Pak. J. Bot*, 39(6), pp.2009-2015.
- Rani, M.A.M.T.A., 2016. Genetic variability and divergence in sunflower (*Helianthus annuus* L.). M. Sc.(Ag.) Thesis submitted to CCSHAU, Hisar.
- Sasikala, M., 2000. Variability studies in interspecific hybrid derivatives of sunflower. M. Sc.(Agri.) Thesis, Tamil Nadu Agricultural University, Coimbatore.
- Sasikala, R., Santhiya, V., Susmitha, D. and Kalaimagal, T., 2025. Genetic Variability, Path Coefficient, and Multivariate Analysis of Seed Yield and its Associated Traits in Sunflower (*Helianthus annuus* L.). *Madras Agricultural Journal*, 112(4), pp.165-171.

- Velazquez, L., Alberdi, I., Paz, C., Aguirrezábal, L. and Pereyra Irujo, G., 2017. Biomass allocation patterns are linked to genotypic differences in whole-plant transpiration efficiency in sunflower. *Frontiers in plant science*, 8, p.1976.
- SAKHARAM, D.F., EVALUATION OF SUNFLOWER (*Helianthus annuus* L.) GENOTYPES FOR SELF-COMPATIBILITY OVER TWO SEASONS.
- Marin, V., Epure, L.I., Ion, N. and Ion, V., 2025. Correlation of sunflower yield with head yielding elements according to row spacing and plant density.
- Markulj Kulundžić, A., Iljkić, D. and Varga, I., 2025. Screening of Sunflower Hybrids Using Physiological and Agronomic Traits. *Agronomy*, 15(9), p.2181.
- Pekcan, V., Yilmaz, M.I., Evci, G., Cil, A.N., Sahin, V., Gunduz, O., Koc, H. and Kaya, Y., 2022. Oil content determination on sunflower seeds in drought conditions. *Journal of Food Processing and Preservation*, 46(10), p.e15481.
- Lagiso, T.M., Singh, B.C.S. and Weyessa, B., 2021. Evaluation of sunflower (*Helianthus annuus* L.) genotypes for quantitative traits and character association of seed yield and yield components at Oromia region, Ethiopia. *Euphytica*, 217(2), p.27.
- Falchi, R., Bonghi, C., Drincovich, M.F., Famiani, F., Lara, M.V., Walker, R.P. and Vizzotto, G., 2020. Sugar metabolism in stone fruit: source-sink relationships and environmental and agronomical effects. *Frontiers in plant science*, 11, p.573982.
- Fernie, A.R., Bachem, C.W., Helariutta, Y., Neuhaus, H.E., Prat, S., Ruan, Y.L., Stitt, M., Sweetlove, L.J., Tegeder, M., Wahl, V. and Sonnewald, S., 2020. Synchronization of developmental, molecular and metabolic aspects of source-sink interactions. *Nature plants*, 6(2), pp.55-66.
- Al-Ashkar, I., Al-Suhaibani, N., Abdella, K., Sallam, M., Alotaibi, M. and Seleiman, M.F., 2021. Combining genetic and multidimensional analyses to identify interpretive traits related to water shortage tolerance as an indirect selection tool for detecting genotypes of drought tolerance in wheat breeding. *Plants*, 10(5), p.931.
- Bojarian, M., Asadi-Gharneh, H.A. and Golabadi, M., 2019. Factor analysis, stepwise regression and path coefficient analyses of yield, yield-associated traits, and fruit quality in tomato. *International Journal of Vegetable Science*, 25(6), pp.542-553.
- Devi, K.R., Chandra, B.S., Lingaiah, N., Hari, Y. and Venkanna, V., 2017. Analysis of variability, correlation and path coefficient studies for yield and quality traits in rice (*Oryza Sativa* L.).
- Aman, J., Bantte, K., Alamerew, S. and Sbhatu, D.B., 2020. Correlation and path coefficient analysis of yield and yield components of quality protein maize (*Zea mays* L.) hybrids at Jimma, western Ethiopia. *International Journal of Agronomy*, 2020(1), p.9651537.
- Martínez-Vilalta, J., García-Valdés, R., Jump, A., Vilà-Cabrera, A. and Mencuccini, M., 2023. Accounting for trait variability and coordination in predictions of drought-induced range shifts in woody plants. *New Phytologist*, 240(1), pp.23-40.
- Radić, V., Balalić, I., Jaćimović, G., Krstić, M., Jocković, M. and Jocić, S., 2021. A study of correlations and path analyses of some traits in sunflower parental lines. *Ratarstvo i povrtarstvo/Field and Vegetable Crops Research*, 58(1), pp.7-13.
- Markulj Kulundžić, A., Iljkić, D. and Varga, I., 2025. Screening of Sunflower Hybrids Using Physiological and Agronomic Traits. *Agronomy*, 15(9), p.2181.

- OlaOlorun, B.M., Shimelis, H., Laing, M. and Mathew, I., 2021. Development of wheat (*Triticum aestivum* L.) populations for drought tolerance and improved biomass allocation through Ethyl Methanesulphonate mutagenesis. *Frontiers in Agronomy*, 3, p.655820.
- Homulle, Z., George, T.S. and Karley, A.J., 2022. Root traits with team benefits: understanding belowground interactions in intercropping systems. *Plant and Soil*, 471(1), pp.1-26.
- Mathew, I., Shimelis, H., Mutema, M., Clulow, A., Zengeni, R., Mbava, N. and Chaplot, V., 2019. Selection of wheat genotypes for biomass allocation to improve drought tolerance and carbon sequestration into soils. *Journal of Agronomy and Crop Science*, 205(4), pp.385-400.
- Bhat, M.A., Mishra, A.K., Jan, S., Bhat, M.A., Kamal, M.A., Rahman, S., Shah, A.A. and Jan, A.T., 2023. Plant growth promoting rhizobacteria in plant health: a perspective study of the underground interaction. *Plants*, 12(3), p.629.
- Awais, M., Wajid, A., Bashir, M.U., Habib-ur-Rahman, M., Raza, M.A.S., Ahmad, A., Saleem, M.F., Hammad, H.M., Mubeen, M., Saeed, U. and Arshad, M.N., 2017. Nitrogen and plant population change radiation capture and utilization capacity of sunflower in semi-arid environment. *Environmental Science and Pollution Research*, 24(21), pp.17511-17525.
- Ren, W., Li, X., Liu, T., Chen, N., Xin, M., Qi, Q. and Liu, B., 2025. Controlled-release fertilizer affects leaf nitrogen allocation and photosynthesis to improve nitrogen use efficiency and yield in the sunflower field. *Frontiers in Plant Science*, 16, p.1622766.
- Veiter, L., Rajamanickam, V. and Herwig, C., 2018. The filamentous fungal pellet–relationship between morphology and productivity. *Applied microbiology and biotechnology*, 102(7), pp.2997-3006.
- Jocković, M., Jocić, S., Cvejić, S., Dedić, B., Jocković, J., Ćuk, N., Radanović, A., Marjanović Jeromela, A., Miklič, V. and Miladinović, D., 2024. Unveiling sunflower morphological and phenological adaptations to drought stress. *OCL*, 31, p.29.
- Gallegos-Cedillo, V.M., Diáñez, F., Nájera, C. and Santos, M., 2021. Plant agronomic features can predict quality and field performance: a bibliometric analysis. *Agronomy*, 11(11), p.2305.
- Lambers, H., Oliveira, R.S. and Pons, T.L., 2019. Growth and allocation. In *Plant physiological ecology* (pp. 385-449). Cham: Springer International Publishing.
- Tahir, A., Iqbal, M.A., Saif, R., Qadir, M. and Sultana, R., 2019. Correlation and path coefficient analysis for morphological and biochemical parameters in sunflower (*Helianthus annuus* L.). *Helia*, 42(70), pp.61-72.
- Komel, S. and Razzaq, A., 2019. Association among morphological and yield related traits in different accessions of sunflower (*Helianthus annuus* L.). *Russian Agricultural Sciences*, 45(2), pp.128-136.
- Jan, M.F., Li, M., Liu, C., Liaqat, W., Altaf, M.T., Barutçular, C. and Baloch, F.S., 2025. Multivariate analysis of root architecture, morpho-physiological, and biochemical traits reveals higher nitrogen use efficiency heterosis in maize hybrids during early vegetative growth. *Plants*, 14(3), p.399.
- Aloui, K., Bouhlal, O., Choukri, H., Gupta, P., El Bouhmadi, K., El Haddad, N., El Bargui, K., Maalouf, F. and Kumar, S., 2025. Effects of Salinity Stress on Grasspea (*Lathyrus sativus* L.) and Its Wild Relatives: Morpho-Physiological Insights at the Seedling Stage. *Plants*, 14(11), p.1666.

- Mariyam, N., Kulkarni, V.V., Sujatha, M. and Tembhurne, B.V., 2024. Assessment of genetic variability and character associations in sunflower (*Helianthus annuus* L.) yield related traits. *Asian Journal of Soil Science and Plant Nutrition*, 10(1), pp.320-327.
- Rana, A.W., Gill, S. and Akram, I., 2022. Promoting oil seed crops in Pakistan: Prospects and constraints. *Intl Food Policy Res Inst*.
- Casadebaig, P., Gauffreteau, A., Landré, A., Langlade, N.B., Mestries, E., Sarron, J., Trépos, R., Vincourt, P. and Debaeke, P., 2022. Optimized cultivar deployment improves the efficiency and stability of sunflower crop production at national scale. *Theoretical and Applied Genetics*, 135(11), pp.4049-4063.
- Rauf, S., Jamil, N., Tariq, S.A., Khan, M., Kausar, M. and Kaya, Y., 2017. Progress in modification of sunflower oil to expand its industrial value. *Journal of the Science of Food and Agriculture*, 97(7), pp.1997-2006.
- Mu, J., Wang, J., Ma, R., Lv, Z., Dong, H., Liu, Y., Duan, W., Liu, S., Wang, P. and Zhang, X., 2025. Optimizing sunflower cultivar selection under climate variability: evidence from coupled meteorological-growth modeling in arid Northwest China. *Agronomy*, 15(7), p.1724.
- Begna, T., 2021. Role and economic importance of crop genetic diversity in food security. *International Journal of Agricultural Science and Food Technology*.
- Swarup, S., Cargill, E.J., Crosby, K., Flagel, L., Kniskern, J. and Glenn, K.C., 2021. Genetic diversity is indispensable for plant breeding to improve crops. *Crop Science*, 61(2), pp.839-852.
- Radanović, A., Miladinović, D., Cvejić, S., Jocković, M. and Jocić, S., 2018. Sunflower genetics from ancestors to modern hybrids—A review. *Genes*, 9(11), p.528.
- Kumar, A., Pandey, D. and Prasad, B., 2018. Correlation and path coefficient analysis for yield and its attributing traits in bread wheat (*Triticum aestivum* L. em Thell). *Journal of Applied and Natural Science*, 10(4), pp.1078-1084.